

# A Comparison of Stellar Extinction and Space-Based Measurements of Stratospheric Aerosol Optical Depth

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**ABSTRACT.** Observed increases of stellar extinction after the two largest recent volcanic eruptions (El Chichón 1982 and Pinatubo 1991) are compiled here from published sources and compared with space-based measurements of stratospheric aerosol optical depth. Hemispheric and global annual mean optical depths following the two eruptions show close agreement between the two methods, if allowance is made for the fact that the stellar extinction data refer only to midlatitudes.

## 1. INTRODUCTION

Large volcanic eruptions are capable of injecting several megatons of sulfurous gases into the stratosphere. These gases react with water vapor and a few other chemical species to form sulfuric acid aerosols. As measured from the ground, the extinction of sunlight and starlight increases as a result of the rise of stratospheric aerosol optical depth (AOD) caused by backscattering into space of some of the incident light by submicron-sized aerosols. Such abrupt increases have been occasionally noted since 1883, by pyrheliometry; since 1963, by stellar photometry, solar photometry, and lidar (optical radar); and since 1979, by space-based instrumentation (Sun photometers and lidars) on board both aircraft and artificial satellites.

Although space-based remote sensing can cover wide swaths of the Earth, it is still necessary to validate the space-based data by using accurate observations from the Earth's surface. Such validations, to date, have been made almost entirely by Sun photometers and lidars located on the ground. The errors in the final space-based AODs, however, come not only from ground observational errors, but also from the large-scale geographical and temporal interpolations necessitated by the incomplete surface and space observations. The lidar AODs themselves are indirectly measured and need to be verified from solar photometric or stellar photometric data. To an extent that seems to have been not fully recognized, the solar photometric observations from one ground station, Mauna Loa, Hawaii ( $20^{\circ}\text{N}$ ,  $156^{\circ}\text{W}$ ), largely underpin the space-based AODs before the late 1990s (Kent & McCormick 1988; Russell et al. 1996). After that date, a worldwide network of Sun photometers (AERONET) was established and began operation; however, the AERONET Sun photometers themselves need to be calibrated against the Mauna Loa instruments (Holben et al. 2001).

In this uncertain situation, it is justifiable to question the accuracy of the space-based AODs that have been obtained following the two largest volcanic eruptions since 1979: those

of El Chichón, Mexico (1982 March); and Pinatubo, Philippines (1991 June). We can here check the space-based AODs by utilizing published stellar photoelectric extinction measurements at two astronomical observatories in the Northern Hemisphere and three in the Southern Hemisphere. Such a check is important, because the stratospheric AODs are the main ingredient needed to study the effects of volcanic eruptions on the Earth's climate through the use of computer-generated general circulation models.

Although the number of stations reporting adequate measurements of stellar extinction is disappointingly small, this has been historically the case (Stothers 2001). The number of stations in the case of the last four major eruptions is 6 for Agung (1963), 4 for Fuego (1974), 2 for El Chichón (1982), and 5 for Pinatubo (1991). However, the quality of the data obtained is very high.

## 2. STELLAR EXTINCTION DATA

Observatory stations providing published stellar extinction data are listed in Table 1. Their geographical locations and the time periods during which accurate stellar extinction measurements were obtained are also listed. At only five of these stations, however, have enough data been acquired to form annual averages of the visual ( $\lambda = 0.55 \mu\text{m}$ ) stellar extinction perturbations,  $a_{\text{vis}}$ , for which the estimated errors are as small as  $\pm 0.01$  mag or less. Nevertheless, all 10 stations show clear detections of the volcanic perturbations to the stratosphere after El Chichón and Pinatubo.

The way in which we have proceeded to obtain  $a_{\text{vis}}$  is as follows. For each station, a baseline of average background stellar extinction is derived on a monthly or annual basis, so far as the observations allow, by using the volcanically undisturbed years. (Night-to-night variability can occasionally be so large that, at a minimum, monthly averages are needed to reduce the effect of fluctuations; in any case, obvious spikes due to dust and smoke

TABLE 1  
STATIONS WITH PUBLISHED STELLAR EXTINCTION DATA AFTER 1978

Station	Country	Latitude	Longitude	Period	Sources of Data
Cerro Tololo .....	Chile	30°S	71°W	1980–1984	Gutiérrez-Moreno et al. 1982; 1986
Flagstaff, AZ .....	United States	35°N	112°W	1972–1996	Lockwood & Thompson 1986; Thompson & Lockwood 1996
Jena .....	Germany	51°N	11°E	1968–1992	Reimann et al. 1992
Kitt Peak, AZ .....	United States	32°N	112°W	1959–1991	Pilachowski et al. 1991
La Silla .....	Chile	29°S	71°W	1975–1997	Rufener 1986; Sterken & Manfroid 1992; Grothues & Gochermann 1992; Burki et al. 1995; Schwartz 2005
Mount John .....	New Zealand	44°S	170°E	1987–1994	Forbes et al. 1995
San Juan .....	Argentina	32°S	69°W	1991–1992	Gil-Hutton 1993
San Pedro Martir .....	Mexico	31°N	115°W	1973–1999	Schuster & Guichard 1985; Schuster & Parrao 2001
Sutherland .....	South Africa	32°S	21°E	1991–1994	Kilkenny 1995
Zacatecas .....	Mexico	23°N	103°W	1977–1983	Schuster et al. 1985

events have been omitted.) Since seasonal changes at good observing sites turn out to be small in comparison to other uncertainties, the use of an annual average extinction instead of the preferred monthly averages is generally adequate if monthly averages are unavailable. Baseline years adopted here are the following: for Flagstaff, 1976–1980, 1986–1991 (Lockwood & Thompson 1986; Thompson & Lockwood 1996); for San Pedro Martir, 1985–1991, 1995–1999 (Schuster & Parrao 2001); for La Silla, 1981, 1990–1991 (Burki et al. 1995); for Sutherland, 1991 (Kilkenny 1995); and for Mount John, 1987–1991 (Forbes et al. 1995). In the case of 1991, only the pre-June data are used.

The average background extinction is then subtracted from the annual average extinctions for the volcanically disturbed years 1983, 1984, 1992, 1993, and 1994. It is assumed that the mean tropospheric component remains the same from year to year, even during volcanically disturbed periods. What is left after the subtraction is the stratospheric stellar extinction perturbation. Derived values of  $a_{\text{vis}}$  are presented in Table 2.

Keeping in mind the very limited latitudinal coverage of the stellar extinction data (31°–35°N and 29°–44°S), we have formed “hemispheric” and “global” averages. The unknown longitudinal distribution is of no real consequence because zonal winds in the stratosphere spread the volcanic aerosols nearly uniformly in longitude within a few weeks after the eruption.

To compare the stellar extinction data with published space-based data, we have converted  $a_{\text{vis}}$  to AOD ( $\tau_{\text{vis}}$ ) by using the relation (Hardie 1962)

$$\tau_{\text{vis}} = 0.921 a_{\text{vis}}.$$

The results are displayed in Table 3.

### 3. SPACE-BASED DATA

Space-based AODs obtained in the aftermath of El Chichón’s eruption represent a composite of measurements made from various airborne instruments and from the Stratospheric Aerosol Measurement II (SAM II) Sun photometer on board the *Nimbus* 7 satellite, which views mostly the Earth’s polar regions. This large eruption occurred during 1982 March at 17°N. Mass loading of the stratosphere probably peaked in August or September, but the aerosol cloud only became global, with a marked concentration in the Northern Hemisphere, by the end of the year (Kent & McCormick 1988). The remarkable hemispheric asymmetry persisted during subsequent years. Kent & McCormick (1988) also found a long-lasting but diminishing concentration of aerosols in a wide equatorial band and within both polar regions even after 1982. However, the latitudinal distribution in each hemisphere appears to be rather more uniform in the two studies by Spinhirne & King (1985) and Sato et al. (1993).

The integrated AODs over an entire hemisphere and over a whole year would seem, therefore, to be more robust numbers to work with in the present context. These have been derived by Sato et al. (1993) and are listed here in Table 3. Within the small estimated errors of the two independent data sets, the stellar extinction AODs and the space-based AODs after El Chichón are in virtually perfect agreement.

Turning now to the eruption of Mount Pinatubo at 15°N during 1991 June, the space-based data consist primarily of satellite measurements taken by the Stratospheric Aerosol and Gas Experiment II (SAGE II) sensors, supplemented by observations made by the Advanced Very High Resolution Radiometer

TABLE 2  
ANNUAL MEAN STELLAR EXTINCTION PERTURBATIONS

Latitude	Station	$a_{\text{vis}}$				
		1983	1984	1992	1993	1994
35°N .....	Flagstaff	0.07	0.02	0.09	0.03	0.02
31°N .....	San Pedro Martir	...	...	0.10	0.03	0.01
29°S .....	La Silla	0.03	0.02	0.07	0.05	0.01
32°S .....	Sutherland	...	...	0.07	0.03	0.01
44°S .....	Mount John	...	...	0.11	0.07	...

TABLE 3  
ANNUAL MEAN STRATOSPHERIC AOD PERTURBATIONS

Method	Hemisphere	$\tau_{\text{vis}}$				
		1983	1984	1992	1993	1994
Stellar Extinction <sup>a</sup>	Northern	0.07	0.02	0.09	0.03	0.01
	Southern	0.03	0.02	0.08	0.05	0.01
	Global	0.05	0.02	0.09	0.04	0.01
Space-Based	Northern	0.07	0.02	0.12	0.05	0.02
	Southern	0.04	0.01	0.12	0.05	0.02
	Global	0.05	0.02	0.12	0.05	0.02
Difference	Northern	0.00	0.00	-0.03	-0.02	-0.01
	Southern	-0.01	+0.01	-0.04	0.00	-0.01
	Global	0.00	0.00	-0.03	-0.01	-0.01

<sup>a</sup> Only latitudes 31°–35°N and 29°–44°S.

(AVHRR) and the SAM II instrument. These data reveal that stratospheric mass loading peaked in late 1991, and by the end of the year had spread globally. The worldwide distribution, though nonuniform, appears to be essentially symmetrical between the two hemispheres (McCormick et al. 1995). Although McCormick et al. (1995) detected significant aerosol concentrations near the equator and the two poles, such a nonuniform aspect of the latitudinal distribution does not appear very strongly after 1992 in Kinnison et al. (1994) and Russell et al. (1996). The satellite AODs are found to agree well with measurements from the Ames airborne Sun photometer (Russell et al. 1996) and from ground-based lidars (Stenchikov et al. 1998; Antuña et al. 2003). However, as we have already mentioned, the primary validation has been mostly established, directly or indirectly, through Sun photometer measurements at Mauna Loa Observatory (Dutton et al. 1994).

Annual mean AODs derived from SAGE II satellite observations (Hansen et al. 1996) are presented in Table 3. Compared to the stellar extinction AODs, they show a slight excess, although for 1993 and 1994 the systematic offset of 0.01 is perhaps not statistically significant. For 1992, however, the difference of 0.03 is too large to ignore. Recognizing that the “hemispheric” and “global” average AODs based on stellar extinction data are derived from observations made only at midlatitudes, we would expect to find a deficit in the years 1991 and 1992 by omitting the large equatorial reservoir of aerosols. Examination of Plate 1 in Russell et al. (1996) confirms that the midlatitude satellite AODs in the visual band agree well with the corresponding stellar extinction values. An analogous explanation can easily account for the much smaller deficits detected in 1993 and 1994.

#### 4. CONCLUSION

Stellar extinction values of stratospheric AOD after the eruptions of El Chichón and Pinatubo agree very well with space-based values, when allowance is made for the limited geographical distribution of the astronomical observatories providing the stellar extinction data. Several conclusions can be drawn from this agreement.

First, the calibration of the space-based values (which ultimately depends on Sun photometer measurements made at Mauna Loa) is independently verified.

Second, the latitudinal bias of the astronomical observatories (which are concentrated in the midlatitudes of each hemisphere) needs to be explicitly reckoned with when forming hemispheric and global averages of AOD. This is important in the case of eruptions in the presatellite past. For example, the “global” mean stratospheric AODs during the period 1883–1963 come almost entirely from northern midlatitude surface pyrheliometric observations. Other observational methods pertaining to this period, such as sulfate acidity measurements in dated Arctic and Antarctic ice cores, can provide some information about the spread of aerosols to the Southern Hemisphere, but are indirect.

Third, the usefulness of stellar extinction observations in the aftermath of large volcanic eruptions remains important today, even with the existence of AERONET. The reason is that independent methods can provide a useful confirmation of the ground calibration if it has been otherwise established by only a single method.

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#### REFERENCES

- Antuña, J. C., et al. 2003, *J. Geophys. Res.*, 108, D20, 4624  
 Burki, G., et al. 1995, *A&AS*, 112, 383  
 Dutton, E. G., Reddy, P., Ryan, S., & DeLuisi, J. J. 1994, *J. Geophys. Res.*, 99, 8295  
 Forbes, M. C., et al. 1995, *Observatory*, 115, 29  
 Gil-Hutton, R. 1993, *Rev. Mex. AA*, 25, 91  
 Grothues, H.-G., & Goehermann, J. 1992, *Messenger*, 68, 43  
 Gutiérrez-Moreno, A., Moreno, H., & Cortés, G. 1982, *PASP*, 94, 722

- \_\_\_\_\_. 1986, PASP, 98, 1208
- Hansen, J., et al. 1996, in *The Mount Pinatubo Eruption Effects on the Atmosphere and Climate*, ed. G. Fiocco, D. Fuà, & G. Visconti (Berlin: Springer), 233
- Hardie, R. H. 1962, in *Astronomical Techniques*, ed. W. A. Hiltner (Chicago: Univ. Chicago Press), 178
- Holben, B. N., et al. 2001, J. Geophys. Res., 106, 12067
- Kent, G. S., & McCormick, M. P. 1988, Optics News, 14, 5, 11
- Kilkenny, D. 1995, Observatory, 115, 25
- Kinnison, D. E., Grant, K. E., Connell, P. S., Rotman, D. A., & Wuebbles, D. J. 1994, J. Geophys. Res., 99, 25705
- Lockwood, G. W., & Thompson, D. T. 1986, AJ, 92, 976
- McCormick, M. P., Thomason, L. W., & Trepte, C. R. 1995, Nature, 373, 399
- Pilachowski, C., Landolt, A., Massey, P., & Montani, J. 1991, NOAO Newsletter, 28, 26
- Reimann, H.-G., Ossenkopf, V., & Beyersdorfer, S. 1992, A&A, 265, 360
- Rufener, F. 1986, A&A, 165, 275
- Russell, P. B., et al. 1996, J. Geophys. Res., 101, 18745
- Sato, M., Hansen, J. E., McCormick, M. P., & Pollack, J. B. 1993, J. Geophys. Res., 98, 22987
- Schuster, W. J., & Guichard, J. 1985, Rev. Mex. AA, 11, 7
- Schuster, W. J., & Parrao, L. 2001, Rev. Mex. AA, 37, 187
- Schuster, W. J., Parrao, L., González Bedolla, S. F., Ríos Herrera, M., & Ríos Berumen, M. 1985, Rev. Mex. AA, 11, 55
- Schwartz, R. D. 2005, J. Geophys. Res., 110, D 14210
- Spinharne, J. D., & King, M. D. 1985, J. Geophys. Res., 90, 10607
- Stenchikov, G. L., et al. 1998, J. Geophys. Res., 103, 13837
- Sterken, C., & Manfroid, J. 1992, A&A, 266, 619
- Stothers, R. B. 2001, J. Geophys. Res., 106, 2993
- Thompson, D. T., & Lockwood, G. W. 1996, Geophys. Res. Lett., 23, 3349